The bound on the mass of the new gauge boson Z' from the process $\mu \longrightarrow 3e$

Chongxing Yue[(a,b)], Guoli Liu[b], Jiantao Li[b]

a: CCAST (World Laboratory) P.O. BOX 8730. B.J. 100080 P.R. China

b: Department of Physics, Henan Normal University, Xingxiang 453002. P.R.China *†

February 1, 2008

Abstract

The new gauge boson Z' predicted by the strong top dynamical symmetry breaking models has significant contributions to the lepton flavor changing process $\mu \longrightarrow 3e$. We consider the bound on the mass of the new gauge boson Z' from the experimental value of the branching ratio $Br(\mu \longrightarrow 3e)$ in the framework of topcolor assisted technicolor models. We find that the precision experimental value of $Br(\mu \longrightarrow 3e)$ gives a severe bound on the Z' mass $M_{Z'}$. For $k_1 \leq 1$, $M_{Z'}$ must be larger than 1.64 TeV.

PACS number: 14.65.Ha, 14.80.Cp

Keywords: topcolor assisted technicolor models, bound on the mass of the new gauge boson Z', branching ratio $B_r(\mu \longrightarrow 3e)$.

---

*This work is supported by the National Natural Science Foundation of China, the Excellent Youth Foundation of Henan Scientific Committee; and Foundation of Henan Educational Committee.

†E-mail: cxyue@pbulic.xxptt.ha.cn

The generation of a large fermion mass such as $m_t = 175\ GeV$ is a difficult problem in the theories of dynamical electroweak symmetry (EWS) breaking. Technicolor (TC) [1] with an extended technicolor (ETC) [2] can naturally break the EWS to give rise to the weak gauge boson masses and also generate the masses of ordinary quarks and leptons. However, ETC models can not explain the top quark's large mass without running afoul of the experimental constraints from the parameter T and the $Z \longrightarrow b\bar{b}$ branching ratio R_b [3]. Top quark condensation models [4] try to identify all of the EWS breaking with the formation of a dynamical top quark mass, but this requires a very large scale $\Lambda \sim 10^{15} GeV$ for the new dynamics and significant fine tuning.

The large mass of the top quark suggests that it may play a special role in the dynamics of the EWS breaking and flavor symmetry breaking. The topcolor assisted technicolor (TC2) models [5], the top see-saw models [6] and the flavor universal coloron models [7] are three of such examples. These models predict the existence of colored gauge bosons (topgluons, colorons), color-singlet gauge boson (Z'), Pseudo Goldstone bosons (technipions and top-pions), and heavy fermions. These new particles can be seen as characteristics of these models. Studying the effects of these new particles in various process will be of particular interest.

The new strong or flavor interactions may exist at relatively low scales and may play an integral part in either EWS breaking or fermion mass generation. Thus, it is interesting to study current experimental bounds on the mass of the corresponding gauge bosons. Ref.[8] gives the limits on the mass of the new gauge bosons Z' via studying its corrections to the precisely measured electroweak quantities at LEP and its effects on bijet production and single top production at Tevatron. In this letter, we will discuss the bounds on the mass of the new gauge boson Z' from the lepton flavor changing process $\mu \longrightarrow 3e$ in the framework of TC2 models. Our results show that the precision experimental value of $B_r(\mu \longrightarrow 3e)$ gives a severe bound on the Z' mass $M_{Z'}$. For the parameter $k_1 \leq 1$, $M_{Z'}$ must be larger than the 1.64 TeV. This is consistent with the limit obtained in Ref.[8].

In the standard model (SM), because of the strong GIM suppression, the tree-level flavor changing neutral currents are absent. Lepton flavor changing processes are strongly

suppressed by powers of small neutrino masses. This opens the possibility of using the corresponding flavor changing process to probe new physics, whose effects may include appreciable violation of neutral flavor conservation already probed by present high energy colliders. The underlying interactions in the strong top dynamical symmetry breaking models (such as TC2 models and top see-saw models) are non-universal and therefore do not possess a GIM mechanism. This is an essential feature of this kind of models due to the need to single out the top quark for condensation. When the non-universal interactions are written in the mass eigenstates, it may lead to the flavor change coupling vertices of the new gauge bosons, such as $Z'tc$, $Z'\mu e$, $Z'\mu\tau$. Thus, the new gauge boson Z' may have significant contributions to some lepton flavor changing processes. The lepton flavor changing processes may have severe bound on the mass $M_{Z'}$ of the Z'. Thus, we can give the bound on the mass $M_{Z'}$ of the Z' via discussing its contributions to these lepton flavor changing processes.

At present, the branching ratios of the lepton flavor changing μ decay processes, such as $\mu \rightarrow 3e$, $\mu \rightarrow e\gamma$ and $\mu \rightarrow e\gamma\gamma$, have been measured precisely. There are severe bounds on these decay processes, i.e. $Br(\mu \rightarrow 3e) \leq 10^{-12}$, $Br(\mu \rightarrow e\gamma) \leq 4.9 \times 10^{-11}$, $Br(\mu \rightarrow e\gamma\gamma) \leq 10^{-10}$[9]. The Z' have no contributions to the processes $\mu \rightarrow e\gamma$ and $\mu \rightarrow e\gamma\gamma$, the experimental value of the branching ratios can not give any bound on the $M_{Z'}$. The new gauge boson Z' have contributions to the lepton flavor changing τ decay processes, such as $\tau \rightarrow 3e$, $\tau \rightarrow e\mu\mu$, etc. Compared to the process $\mu \rightarrow 3e$, however, the experimental bounds on these processes are weaker. The branching ratios are of order 10^{-6}[9]. Thus, in this paper, we will concentrate on the bound on the $M_{Z'}$ from the lepton flavor changing process $\mu \rightarrow 3e$.

In TC2 models, the ETC interactions have contributions to all quark and lepton masses, while the mass of the top quark is mainly generated by the topcolor interactions, and EWSB is driven by technicolor or a Higgs sector. To maintain electroweak symmetry between top and bottom quarks and yet not generate $m_b \simeq m_t$, the topcolor gauge group is usually taken to be a strongly coupled $SU(3) \otimes U(1)$. The $U(1)$ provides the difference that causes only top quarks to condense. At the $\Lambda \sim 1TeV$, the dynamics of a general

TC2 model involves the following structure [5, 10]:

$$SU(3)_1 \otimes SU(3)_2 \otimes U(1)_{y_1} \otimes U(1)_{y_2} \times SU(2)_L \longrightarrow SU(3)_{QCD} \otimes U(1)_{EM} \tag{1}$$

where $SU(3)_1 \otimes U(1)_{y_1}$ ($SU(3)_2 \otimes U(1)y_2$) generally couples preferentially to the third (first and second) generations. The $U(1)_{y_i}$ are just strongly rescaled versions of electroweak $U(1)_y$. This breaking scenario gives rise to the topcolor gauge bosons including the color-octet coloron B_μ^A and color-singlet extra $U(1)$ gauge boson Z'. The coupling of the new gauge boson Z' and B_μ^A to ordinary fermions can be written as :

$$\mathcal{L}_{Z'} = g_1 cot\theta' Z' \cdot J_{Z'}, \qquad \mathcal{L}_B = g_3 cot\theta B^A \cdot J_B^A \tag{2}$$

where $g_3(g_1)$ is the QCD($U(1)_y$) coupling constant at the scale Λ_{TC}, θ and θ' are the mixing angles. To obtain the top quark direction for condensation, we have $cot\theta \gg 1$ and $cot\theta' \gg 1$. Integrating out the heavy bosons Z' and B_μ^A, the couplings (Eq.(2)) give the effective low energy four fermion interactions, which can be written as :

$$\mathcal{L}_{eff,Z'} = -\frac{2\pi k_1}{M_{Z'}^2} J_{Z'} \cdot J_{Z'}, \qquad \mathcal{L}_{eff,B} = -\frac{2\pi k}{M_B^2} J_B^A \cdot J_B^A \tag{3}$$

where $M_{Z'}$ and M_B are the masses of the new gauge boson Z' and B_μ^A, respectively. k_1 and k are coupling constants which can be written as $k_1 = g_1^2 cot^2\theta'/4\pi$, $k = g_3^2 cot^2\theta/4\pi$. In general, the currents $J_{Z'}$ and J_B involve all three generations of fermions:

$$J_Z' = J_{Z',1} + J_{Z',2} + J_{Z',3}, \qquad J_B = J_{B,1} + J_{B,2} + J_{B,3} \tag{4}$$

For the first and second generations, the currents are (in weak eigenbasis):

$$\begin{aligned} J^\mu_{Z',1} &= -\tan^2\theta' \Big(\frac{1}{6}\overline{u_L}\gamma^\mu u_L + \frac{1}{6}\overline{d_L}\gamma_\mu d_L + \frac{2}{3}\overline{u_R}\gamma^\mu u_R \\ &\quad -\frac{1}{3}\overline{d_R}\gamma^\mu d_R - \frac{1}{2}e_L\gamma^\mu e_L - \frac{1}{2}\overline{\nu_{eL}}\gamma^\mu\nu_{eL} - \overline{e_R}\gamma^\mu e_R \ ) \end{aligned} \tag{5}$$

$$\begin{aligned} J^\mu_{Z',2} &= -\tan^2\theta' \Big(\frac{1}{6}\overline{c_L}\gamma^\mu c_L + \frac{1}{6}\overline{s_L}\gamma^\mu s_L + \frac{2}{3}\overline{c_R}\gamma^\mu c_R \\ &\quad -\frac{1}{3}\overline{s_R}\gamma^\mu\overline{s_R} - \frac{1}{2}\mu_L\gamma^\mu\mu_L - \frac{1}{2}\nu_{\mu L}\gamma^\mu\nu_{\mu L} - \mu_R\gamma^\mu\mu_R \ ) \end{aligned} \tag{6}$$

$$J^{\mu}_{B,1} = -\tan^2\theta(\overline{u}\gamma^{\mu}\frac{\lambda^A}{2}u + \overline{d}\gamma^{\mu}\frac{\lambda^A}{2}d) \quad (7)$$

$$J^{\mu}_{B,2} = -\tan^2\theta(\overline{c}\gamma^{\mu}\frac{\lambda^A}{2}c + \overline{s}\gamma^{\mu}\frac{\lambda^A}{2}s) \quad (8)$$

where λ^A is a Gell-Man matrix acting on color indices. From Eq.(7) and Eq.(8), we can see that the gauge bosons B^A_{μ} have no contributions to the lepton flavor changing process $\mu \longrightarrow 3e$. The precision experimental value of $Br(\mu \longrightarrow 3e)$ can not give any bound on the mass M_B of the color-octet coloron B^A_{μ}.

For TC2 models, the underlying interactions, topcolor interactions, are non-universal and therefore do not possess a GIM mechanism. When the non-universal interactions are written in the mass eigenstates, it results in the flavor changing coupling vertices. After rotation to the mass eigenstates, Eq.(3) generates four fermion interactions leading to the flavor changing coupling vertices. For the lepton flavor changing process $\mu \longrightarrow 3e$, the relative effective Lagrangian can be written as:

$$\mathcal{L}'_{eff} = \frac{\pi k_1 \tan^4\theta'}{2M^2_{Z'}}[k_L(\mu_L\gamma^{\mu}e_L)(e_L\gamma_{\mu}e_L) + 2k_R(\mu_R\gamma^{\mu}e_R)(e_R\gamma_{\mu}e_R)] \quad (9)$$

where k_L and k_R are the flavor mixing factors. In the following estimation, we will assume $|k_L| = |k_R| \simeq \lambda$ [10, 11], which λ is the Wolfenstein parameter[12].

Comparing the contributions of the gauge boson Z' to the process $\mu \longrightarrow 3e$ to that of ordinary muon decay $\mu \longrightarrow e\nu\overline{\nu}$, which proceeds via the electroweak gauge boson W exchange, gives the branching ratio $Br(\mu \longrightarrow 3e)$ arising from the Z' exchange:

$$Br(\mu \longrightarrow 3e) = \frac{\Gamma(\mu \longrightarrow 3e)}{\Gamma(\mu \longrightarrow e\nu\overline{\nu})} = \frac{5\alpha_e^2 S_W^4 M_W^4}{64 C_W^8 k_1^2 M_{Z'}^4}A \quad (10)$$

with $A = k_L^2 + 4k_R^2$, $S_W = \sin\theta_W$ and $C_W = \cos\theta_W$, which θ_W is the weinberg angle, α_e is the electromagnetic coupling constant. In our estimation, we will take $\lambda = 0.22$, $\alpha_e = 1/128.9$, $M_W = 80.41\ GeV$ [13]. Using the experimental value $Br(\mu \longrightarrow 3e) \leq 10^{-12}$, we can give the bound on the mass $M_{Z'}$ from Eq.(10). Our results are presented in Fig1. From Fig1, we can see that the lower bound on the mass $M_{Z'}$ increases with decreasing the value of k_1. Considering the requirement of vacuum tilting and the constraints from Z-pole physics and $U(1)$ triviality, there is the region of coupling constant parameter

space which is $k \simeq 2$, $k_1 \leq 1$ for TC2 models [10, 14]. If we take $k_1 = 0.2$, then we have $M_{Z'} \geq 3.68\ TeV$.

From Eq.(10), we can see that the bound on $M_{Z'}$ is sensitive to the values of the flavor mixing factors. To see the effect of the flavor mixing factors on the bound, we plot bound on the mass $M_{Z'}$ as a function of the parameter λ in Fig2 for $k_1 = 1$. From Fig2, we can see that the lower bound on the mass $M_{Z'}$ increases with increasing the value of λ. For $\lambda \geq 0.21$, there must be $M_{Z'} \geq 1.6TeV$.

In this paper, we have discussed the bound on the mass $M_{Z'}$ of the new gauge boson Z' from the experimental value of the branching ratio $Br(\mu \rightarrow 3e)$ in the framework of TC2 models. Our results shows that the precision experimental value of $Br(\mu \rightarrow 3e)$ gives a stringent bound on $M_{Z'}$. The mass $M_{Z'}$ must be larger than $1.64TeV$ for $k_1 \leq 1.0$ and $\lambda = 0.22$.

Figure Captions

Fig.1: The lower bound on the mass $M_{Z'}$ as a function of the parameter k_1. The horizontal line is the bound on the parameter k_1.

Fig.2: The lower bound on the mass $M_{Z'}$ as a function of the parameter $|k_L| = |k_R| = \lambda$ for $k_1 = 1$.

References

[1] S.Weiberg, *Phys.Rev.* D**13**, (1976)974; D**19**, (1979)1277; L.Susskind, *ibid.* D**20**, (1979)2617.

[2] S.Dimopoulos and L.Susskind, *Nucl.Phys.* B**155**, (1979)237; E.Eichten and K.Lane, *Phys.Lett.* B**90**, (1980)125.

[3] T. Appelquist et al., *Phys. Rev. Lett.***53**, (1984)1523; R. S. Chivukula, S. B. Selipsky, and E. H. Simmons, *Phys. Rev. Lett.***69**,(1992)575; Chong-Xing Yue, Yu-Ping Kuang, and Gong-Ru Lu, *J. Phys.* G**23**, (1997)163.

[4] V. A. Miransky, M. Tanabashi and K. Yamawaki, *Phys. Lett.* B**221**,(1989)171; W. A. Bardeen, C. T. Hill and M. Lindner, *Phys.Rev.* D**41**,(1990)1647.

[5] C. T. Hill, *Phys.Lett.* B**345**, (1995)483; K. Lane and E. Eichten, *Phys.Lett.* B**352**, (1995)383; K. Lane, *Phys.Lett.* B**433**, (1998)96.

[6] B.Dobrescu and C. T. Hill, *Phys.Rev.Lett.***81**, (1998)2634; R. S. Chivukula, B. Dobrescu, H. Georgi and C. T. Hill, hep-ph/**9809470**, *Phys.Rev.* D**59**, (1999)075003.

[7] M. B. Popovic and E. H. Simmons, *Phys.Rev.* D**58**, (1998)095007; K. Lane, *Phys.Lett.* B**433**, (1998)96; G. Burdman and N. Evans, *Phys.Rev.* D**59**, (1999)115005.

[8] G. Burdman, R. S. Chivukula, and N. Evans, *Phys.Rev.* D**61**, (2000)035009; G. Burdman, R. S. Chivukula, and N. Evans, hep-ph/**0005098**.

[9] Particle Data Grope, *C. Caso et. al. Europ Phys. J.C* **3**, (1998)1.

[10] G. Buchalla, G. Burdman, C. T. Hill and D. Kominis, *Phys.Rev.* D**53**, (1996)5185.

[11] Hong-Jian He and C.-P. Yuan, *Phys.Rev.Lett.* **83**, (1999)28; G. Burdman, *Phys.Rev.Lett.* **83**, (1999)2888.

[12] L. Wolfenstein, *Phys.Rev.Lett.* **51**, (1983)1945.

[13] R. Alemany et.al.,*Eur. Phys. J. C***2**, (1998)123; M. Davier and A. Hocker, *Phys. Lett. B***419**, (1998)419; J. H. Kuhn and M. Steinhauser, *Phys. Lett. B***437**, (1998)425; J. Erler, *Phys. Rev. D*,**59**, (1999)054008.

[14] W. Loinaz and T. Taheuchi, *Phys.Rev. D***60**, (1999)015005; Chong-Xing Yue, Yu-Ping Kuang, Xue-Lei Wang, Wei-Bin Li, **hep-ph/0001133**, *Phys. Rev. D*,**62**, (2000)055005.

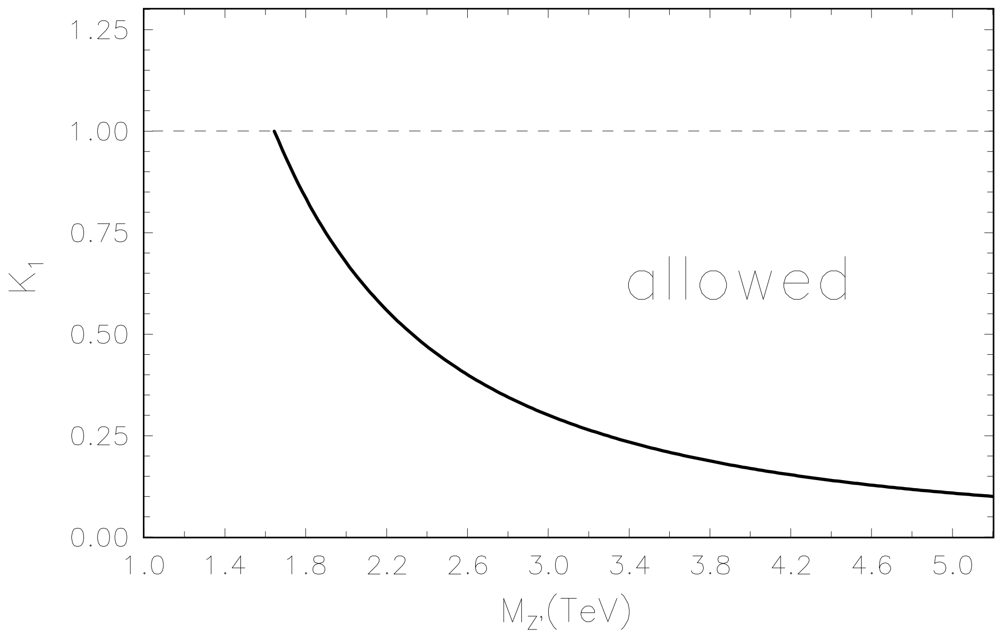
1.25
1.00
0.75
0.50
0.25
0.00
K_1
allowed
1.0 1.4 1.8 2.2 2.6 3.0 3.4 3.8 4.2 4.6 5.0
$M_{Z'}$(TeV)

Fig.1

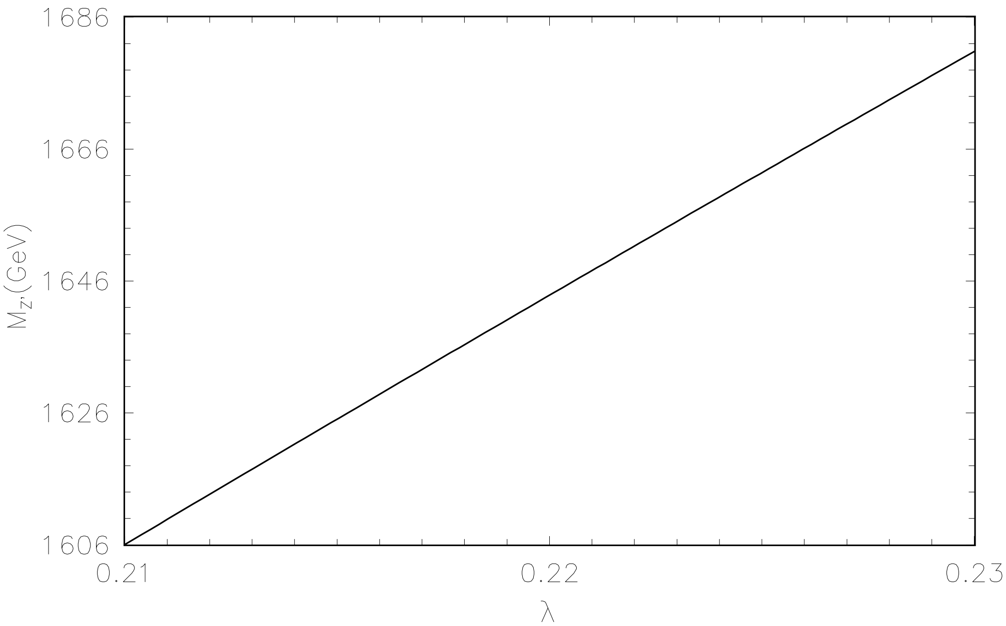
1686
1666
1646
1626
1606
$M_{Z'}$(GeV)
0.21 0.22 0.23
λ

Fig.2